CHAPTER 6

WHAT HAS BEEN THE PERFORMANCE OF IMPROVED GROUND?

Many of the ground improvement methods discussed in this manual have been used for many years in "conventional" applications such as improving the bearing capacity, slope stabilization, increasing the rate of consolidation settlement and improving seepage barriers. Experience over the past several decades has shown that the required performance in most conventional applications can be obtained if the appropriate ground improvement method is selected and the design and construction are done well. Xanthakos et al. (1994) present case histories involving many different types of ground improvement, as well as lists of projects where jet grouting, densification techniques, and micro-piles were used successfully. Case histories are also presented in ASCE (1997). An extensive list of jet grouting projects for different applications is presented in ASCE (1997).

A common "trouble spot" with all types of ground improvment is the difficulty in verifying that the desired level of improvement has been attained. Another difficulty with grouting and deep soil mixing occurs in organic soils. Many grouts and additives used for improving soil require a high pH to set. Organic soils are typically somehat acidic. Therefore, the pH of organic soils may need to be increased if grouting or deep mixing are used.

The use of ground improvement for mitigation of earthquake hazards is relatively new and untested. Therefore, the focus of this chapter is on the performance of improved ground subjected to strong ground motions induced by earthquakes.

While various ground improvement methods have been used at many sites to reduce the settlement and lateral spreading caused by earthquakes, very few of these sites have actually been subjected to strong ground motions. Mitchell et al. (1995) compiled information from more than 30 improved ground sites which experienced large enough earthquake motions that untreated ground liquefied and the effectiveness of various treatment options could be evaluated. The study showed that ground improvement will help prevent liquefaction and ground failure from occurring and reduce the amount of settlement and lateral displacement that can occur if liquefaction does occur.

The 32 cases studied were located in California and Japan. The California sites were subjected to the 1989 Loma Prieta or the 1994 Northridge earthquake. The Japanese earthquakes included the 1964 Niigata earthquake and the 1995 Hyogoken Nambu (Kobe) earthquake, as well as three lesser known earthquakes (1968 Tokachi-Oki, the 1978 Miyagi-Ken-Oki, the 1993 Kushiro-Oki, and the 1994 Hokkaido-Toho-Oki earthquakes). The magnitudes of these earthquakes ranged from about 6.9 to 8.3. The local ground surface accelerations at the individual sites ranged from as low as 0.1g to as high as 1.0g. Detailed information on the 1995 Hyogoken-Nambu (Kobe) earthquake is presented in two special issues of Soils and Foundations (Japanese Geotechnical Society, January 1996 and September 1998).

The types of soil that were improved consisted primarily of loose to medium-dense sands and sandy silts, many of which were hydraulic sand fills. Prior to treatment, the average $(N_1)_{60}$ values for the layers requiring treatment ranged from 4 to 23 blows per foot. In most cases, the relative densities after ground improvement were greater than 75 percent, with post-treatment $(N_1)_{60}$ values ranging from about 25 to 30 blows per foot.

Types of ground improvement used included vibrocompaction methods, compaction piles, vibroreplacement stone columns, deep dynamic compaction, gravel drains, compaction grouting and chemical grouting. The predominant method of improvement was vibrocompaction by either vibroflotation or vibrorod. Also included in this study were cases where structures were founded on mix-in-place soil-cement columns instead of conventional deep foundations or improved ground. Use of deep soil mixing for structural support and for mitigation of liquefaction risk are relatively new technologies in the United States.

In studying the 32 case histories, Mitchell et al. (1995) found that in general, improved ground experiences much less settlement and lateral displacement than untreated ground. When founded on improved ground, structures and facilities are much less likely to be damaged than are similar facilities founded on untreated ground. At several sites in California, treated ground and facilities built upon it were not damaged due to shaking during the Loma Prieta earthquake, but adjacent untreated ground experienced severe cracking and/or settlement due to liquefaction. It is important to note that most of these sites experienced ground accelerations and durations of shaking that were less than the design values, so the total performance during the design event was not tested. However, at one site subjected to ground accelerations higher than the design acceleration, no damage was observed. At some improved ground sites in Japan, liquefaction and associated settlement and lateral displacement did occur; however, the deformations were significantly less than the deformations experienced at similar sites where the ground was not treated. Facilities at the treated ground sites experienced significantly less damage than similar facilities on untreated ground.

Mitchell et al. (1995) also noted three sites where the lateral extent of treatment outside the perimeter of structures was less than the recommended distance equal to the depth of treatment. As these locations, site constraints prevented this width of treatment. Damage was observed at all three of the sites.

In cases where the layer to be improved is below a loose fill layer, installation of ground improvement measures or deep foundations may cause improvements to the fill itself through densification and prestressing. At several sites in Japan, preloading and sand drains were used for precompression of a soft clay layer overlain by 12 to 20 m of loose hydraulic fill. The process of sand drain installation was found to increase the SPT resistance of the hydraulic fill by about 2 to 3 blows per 0.3 m (Yasuda et al., 1996). Settlement data categorized by ground improvement method is shown in Figure 45. Although the treatments were designed to improve the clay layer rather than the fill, the plot shows that preloading alone, sand drains alone, and sand drains plus preloading were increasingly effective in reducing the earthquake-induced settlements (Mitchell et al., 1995).

Sites where gravel drains were used for mitigation of liquefaction risk generally performed well when subjected to earthquake shaking. Mitchell et al. (1995) report on several cases in

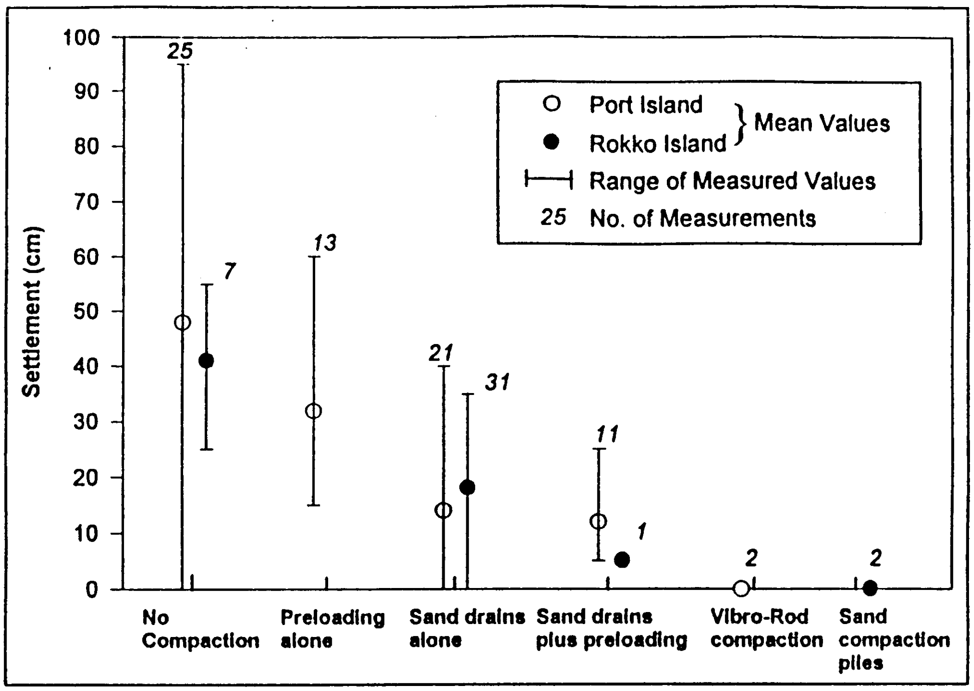

Figure 45. Measured settlements at improved sites due to the 1995 Hyogo-ken Nambu (Kobe) earthquake (after Yasuda et al., 1996).

Japan where gravel drains were used alone or in combination with other improvement techniques. It is not clear if the improvement from gravel drains resulted from dissipation of excess pore pressure or densification of the surrounding ground during installation. Hayden and Baez (1994) surveyed two sites shaken in the 1994 Northridge earthquake where stone columns were used. The structures at both sites were undamaged and there was no evidence of ground distress or liquefaction around the structures.

Mix-in-place soil-cement columns appear to be a viable alternative to deep foundations or ground improvement methods for mitigation of liquefaction risk. Mitchell et al. (1995) reported that eight projects where structures were founded on mix-in-place soil-cement columns performed well in the Kobe earthquake.

When sites are improved to the "no liquefaction" side of liquefaction potential curves, the effects of liquefaction should be relatively minor. At five sites in California and Japan subjected to either the Loma Prieta or the Kobe earthquake, enough data were available to determine pre- and post-densification $(N_1)_{60}$ values throughout the soil profile. In these cases, there was a reasonable correlation between the performance of the site and predictions of performance based on standard cyclic stress ratio - $(N_1)_{60}$ relationships (Mitchell et al. 1995).

Felio et al. (1990) performed detailed post-earthquake observations of eight soil nailed walls subjected to shaking during the 1989 Loma Prieta earthquake. The walls ranged in height from 2.7 to 9.8 m and were subjected to maximum ground surface accelerations between 0.01 and 0.47 g. No cracking or other signs of distress were observed in any of the structures. Based on the results of the observations, Felio et al. (1990) concluded that soil nailed walls perform well when subjected to earthquake loading.